

Gamma-Rays and the Far-Infrared–Radio Continuum Correlation Reveal a Powerful Galactic Centre Wind

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ABSTRACT

We consider the thermal and non-thermal emission from the inner 200 pc of the Galaxy. The radiation from this almost star-burst-like region is ultimately driven dominantly by on-going massive star formation. We show that this region’s radio continuum (RC) emission is in relative deficit with respect to the expectation afforded by the Far-infrared–Radio Continuum Correlation (FRC). Likewise we show that the region’s γ -ray emission falls short of that expected given its star formation and resultant supernova rates. These facts are compellingly explained by positing that a powerful (400–1200 km/s) wind is launched from the region. This wind probably plays a number of important roles including advecting positrons into the Galactic bulge thus explaining the observed \sim kpc extension of the 511 keV positron annihilation signal around the GC. We also show that the large-scale GC magnetic field falls in the range \sim 100–300 μ G and that – in the time they remain in the region – GC cosmic rays do not penetrate into the region’s densest molecular material.

Key words: cosmic rays – ISM: jets and outflows – supernova remnants – Galaxy: centre – radio continuum: ISM – gamma-rays: theory

1 INTRODUCTION

The extreme ISM conditions in the central \sim 200 pc of the Galaxy render the region more akin to a star-bursting system (e.g., Launhardt et al. 2002) than to almost any region in the Galactic disk. The similarities include: i) a high areal star-formation and (consequent) supernova rates; ii) a flatish overall radio spectrum within the star-forming region (cf. Niklas et al. 1997; Thompson et al. 2006); iii) a region surrounding the star-forming nucleus of bright but diffuse, non-thermal radio emission; iv) the existence of diffuse γ -ray emission also apparently associated with star formation (cf. Fermi LAT Collaboration 2009; HESS Collaboration 2009; VERITAS collaboration 2009, on NGC 253 and M82); and v) a rather strong magnetic field ($> 50 \mu$ G; Crocker et al. 2010). Here we argue for another similarity: a strong outflow with a speed 400–1200 km/s (comparable to the escape speed) and energetically consistent with being driven by current star-formation (Veilleux et al. 2005; Strickland & Heckman 2009).

Massive, young stars are copious producers of UV and optical light which is reprocessed into IR emission by the dust of the stars’ natal molecular envelopes (Devereux & Young 1990). On the other hand, cosmic ray (CR) electrons and ions – ultimately powered by supernovae (e.g., Hillas 2005) – produce their own (non-thermal) radiative signatures. These include \sim GHz radio continuum (RC) synchrotron emission and inverse Compton (IC) and bremsstrahlung emission at γ -ray wavelengths by CR electrons and γ -rays from neutral meson decay following hadronic collisions between CR ions and gas.

Given the connection of these radiative processes back to massive ($M_{\star} > 8 M_{\odot}$) star formation (Völk 1989), one might expect that they be globally correlated. Such is observed (Dickey & Salpeter 1984; de Jong et al. 1985; Helou et al. 1985): an extremely tight (dispersion of ~ 0.26 dex; Yun et al. 2001) FIR-RC correlation (FRC) is found (e.g., Condon 1992) to hold over five orders of magnitude in RC luminosity (Yun et al. 2001), and both globally and at sub-galactic scales (Hughes et al. 2006; Tabatabaei et al. 2007). Likewise, one might also expect (Thompson et al. 2006; Thompson et al. 2007) a global scaling between FIR and γ -ray production (‘F γ S’). As we show below, however – and

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in interesting contrast to star-bursting systems (Thompson et al. 2006) – the GC does not fall on these scaling relations: we detect far less non-thermal emission than expected given the region’s star-formation rate. This deficit is ultimately explained by a large-scale, powerful outflow from the region.

2 CORRELATIONS AND SCALINGS

The H.E.S.S. Imaging Air-Cherenkov γ -ray Telescope has detected hard-spectrum, diffuse \sim TeV γ -ray emission surrounding the GC over the region defined by $|l| < 0.8^\circ$ and $|b| < 0.3^\circ$ with an intensity of $1.4 \times 10^{-20} \text{ cm}^{-2} \text{ eV}^{-1} \text{ s}^{-1} \text{ sr}^{-1}$ at 1 TeV (with the point TeV source coincident with Sgr A* subtracted). Only dimmer diffuse TeV emission is detected outside this (hereinafter) ‘HESS field’.

Of note, is that the spectral index, γ , of the GC diffuse \sim TeV emission, where $F_\gamma \propto E_\gamma^{-\gamma}$, is $2.3 \pm 0.07_{\text{stat}} \pm 0.20_{\text{sys}}$, significantly harder than the spectral index of the CR ion population threading the Galactic disk and the diffuse γ -ray emission it generates. Disk CRs experience energy-dependent confinement and their steady-state distribution is, therefore, steepened from the injection distribution into the softer $\sim E^{-2.75}$ spectrum observed at earth (see, e.g., Aharonian et al. 2006). The GC TeV γ -ray spectral index (and that inferred for the parent CR ions) is close to that inferred for the *injection* spectrum of Galactic disk CRs, itself within the reasonable range of ~ 2.1 - 2.2 expected (Hillas 2005) for 1st-order Fermi acceleration at astrophysical shocks.

Empirically the 1.4 GHz RC (spectral) luminosity and the total IR luminosity ($L_{\text{TIR}}[8 - 1000] \mu\text{m}$; Calzetti et al. 2000) are connected as (Yun et al. 2001; Thompson et al. 2007)

$$\nu L_\nu(1.4 \text{ GHz}) \simeq 1.1 \times 10^{-6} L_{\text{TIR}} \quad (1)$$

with a scatter of ~ 0.26 dex. On the basis of IRAS data (Launhardt et al. 2002) the L_{TIR} of the HESS field is $1.6 \times 10^{42} \text{ erg/s}$, implying (Kennicutt 1998) a SFR of $0.08 M_\odot/\text{yr}$ for the HESS field. In useful units, the 1.4 GHz RC luminosity (Reich et al. 1990) of the HESS field is $1.7 \times 10^{35} \text{ erg/s}^{[1]}$, ~ 1.0 dex or $\sim 4\sigma$ short of the expectation from the FRC.

Thompson et al. (2007) use the empirically-established connection between the SFR and the total infrared luminosity to relate the power, injected by supernovae into CRs, to L_{TIR} and hence to *predict* that the TIR and γ -ray emission from luminous star-forming galaxies should scale as

$$\nu L_\nu(\text{GeV}) \simeq 2.0 \times 10^{-5} \eta_{0.10} L_{\text{TIR}} \quad (2)$$

where the proton spectrum is assumed $\propto E_p^{-2}$ up to $E_p^{\text{max}} \simeq 10^{15} \text{ eV}$ and we have renormalized the equation of Thompson et al. (2007) assuming $\eta_{0.10}$ 10% of the 10^{51} ergs per supernova goes into relativistic ions. This relation assumes that the region under consideration is calorimetric to CR ions.

On the basis of the results presented by Meurer (2009),

Fermi observes a luminosity of $\sim 3 \times 10^{36} \text{ erg/s}$ for $E_\gamma > \text{GeV}$ for emission from the central $1^\circ \times 1^\circ$ field, only $\sim 10\%$ of that expected from the FIR emission. The Fermi observations are, however, substantially polluted by line-of-sight and point source emission (including from a source coincident with Sgr A*: Chernyakova et al. 2010) so they only constitute an upper limit to the true diffuse γ -ray emission from the region.

We can consider the HESS data by scaling eq. 2 from $L_\gamma(E_\gamma > \text{GeV})$ to $L_\gamma(E_\gamma > \text{TeV})$. For the TeV spectral index of ~ 2.3 and assuming an hadronic origin to the TeV γ -rays, $L_\gamma(E_\gamma > \text{TeV}) \simeq 0.2 L_\gamma(E_\gamma > \text{GeV})$. The TeV luminosity we infer for the HESS field of $1.2 \times 10^{35} \text{ erg/s}$ (integrating to 100 TeV) is *only $\sim 2\%$ of the prediction from the suitably-scaled version of eq. 2.*

Thus the FRC fails badly in the case of the HESS field: far less RC than expected is detected given its FIR output. Likewise, the γ -ray luminosity of the region is significantly in deficit given the region’s FIR output (and implied star-formation rate). There are three potential explanations of these discrepancies:

Firstly, a RC deficit could arise if a starburst event occurred more recently ($\lesssim 10^7$ years) than the lifetime of the massive stars whose supernova remnants accelerate the CR electrons which generate synchrotron emission. Although we expect some stochastic variation in the GC’s overall SFR, we find, however, that the current SFR is close to the long-term ($\gtrsim 10^7$) average value (cf. Serabyn & Morris 1996; Figer et al. 2004). A strong piece of evidence for this is that a number of other handles on the GC supernova rate we describe in Paper II that are sensitive to long-term average values of this quantity – through, e.g., studies of the region’s pulsar population (Lazio & Cordes 2008) – are consistent with the supernova rate implied by the current SFR as traced by FIR, viz. 0.04/century in the HESS field.

Secondly, it may be that GC SNRs are intrinsically low-efficiency (cf. Erlykin & Wolfendale 2007) CR accelerators (plausible because of their – *on average* – dense environs: Fatuzzo & Melia 2005). However, the detailed numerical modelling set out in Paper II shows that GC supernovae do, indeed, accelerate CRs with typical (e.g., Hillas 2005) efficiency: about 10% of the total 10^{51} erg mechanical energy per supernova goes into non-thermal particles. Given the above rate, this implies that supernovae inject $\sim 10^{39} \text{ erg/s}$ into the GC CR population (cf. Crocker & Aharonian 2010).

Lastly, given the half-height of the region is only $\sim 40 \text{ pc}$, a reasonable reaction to the breakdown of the FRC is that it is unsurprising; many studies (Murgia et al. 2005) find a break-down in the correlation at $\sim \text{kpc}$, often proposed to be due to electron transport. On the other hand, studies, e.g., of the Large Magellanic Cloud (Hughes et al. 2006), the Scd galaxy M33 (Tabatabaei et al. 2007), and within the Milky Way (Zhang et al. 2010) reveal a tight connection between RC and FIR emission down to scales $\lesssim 50 \text{ pc}$.

A potential fourth explanation of why the HESS field falls off the FRC is that power fed into non-thermal electrons is ‘lost’ to ionization and bremsstrahlung and/or inverse Compton emission (Thompson et al. 2006; Thompson et al. 2007) rather than synchrotron emission (plausible because of the GC’s dense gas and radiation environment).

¹ We have removed the contribution from synchrotron emission from relativistic electrons in the Galactic plane but out of the GC: see Crocker, Jones, Aharonian et al. 2010, *to be submitted*, henceforth Paper II.

Given, however, the HESS field also falls short of the F γ S, this explanation is, at least, seriously incomplete.

In summary here, it seems that *CR transport out of the HESS field is by far the most plausible explanation for why it falls off the global scalings discussed*; below we show that the transport mechanism is a wind.

3 PRIOR EVIDENCE FOR AN OUTFLOW FROM THE GC

There is multi-wavelength evidence in support of the existence of GC outflow. Recent infra-red observations show that the GC's massive stellar clusters are blowing a bubble into their environment (e.g., Bally et al. 2010). Keeney et al. (2006) and Zech et al. (2008) have found evidence for high-velocity gas consistent with a GC outflow or fountain in UV absorption features towards, respectively, two AGN and a GC globular cluster. The region's spectacular non-thermal radio filaments (Yusef-Zadeh et al. 1987) may be due to a fast outflow (e.g., Shore & LaRosa 1999). RC evidence of an outflow was found in 10 GHz radio continuum emission by Sofue & Handa (1984) in the form of a $\sim 1^\circ$ (or ~ 140 pc) tall and diameter < 130 pc shell of emission rising north of the Galactic plane called the Galactic Centre lobe (GCL). RC emission from the lobe's eastern part has HI absorption that clearly puts it in the GC region (Lasenby et al. 1989) and its ionized gas has a high metallicity (Law et al. 2009). Filamentary structures coincident with the radio have been discovered at mid-infrared wavelengths (Bland-Hawthorn & Cohen 2003) and the structure interpreted as evidence for a previous episode of either starburst (Bland-Hawthorn & Cohen 2003) or nuclear activity (Melia & Falcke 2001). Law (2010) has found that the formation of the GCL is consistent with currently-observed pressures and rates of star-formation in the central few $\times 10$ pc of the Galaxy. Finally, Law (2010) determined the \sim GHz spectral index of the GCL steepens with increasing distance (both north and south) of the Galactic plane. This constitutes strong evidence for synchrotron ageing of a CR electron population transported out of the plane. Thus, a natural interpretation is that the GCL's RC emission is due to CR electrons advected from the inner GC (essentially the HESS region) on a wind (cf. Zirakashvili & Völk 2006; Heesen et al. 2009, on, e.g., NGC 253 and M82).

This interpretation requires that

- The spectrum of the electrons leaving the HESS region (as given by Eq.3) must match the spectrum *at injection* required for the GCL electrons with spectral index 2.0 – 2.4 (Crocker et al. 2010). This will be well-satisfied if an energy-independent transport process like a wind removes CR electrons – accelerated into an in-situ $\sim E^{-2}$ distribution – from the inner GC.
- The power in electrons leaving the HESS region must be enough to support the GCL electron population, viz. $(3 - 10) \times 10^{37}$ erg/s (Crocker et al. 2010). This is well satisfied given the SN rate in the HESS region.
- The time to transport electrons over the extent of the GCL must be less than the loss time over the same scale. This implies a wind speed of strictly > 150 km/s and probably $\gtrsim 300$ km/s: see fig. 1.

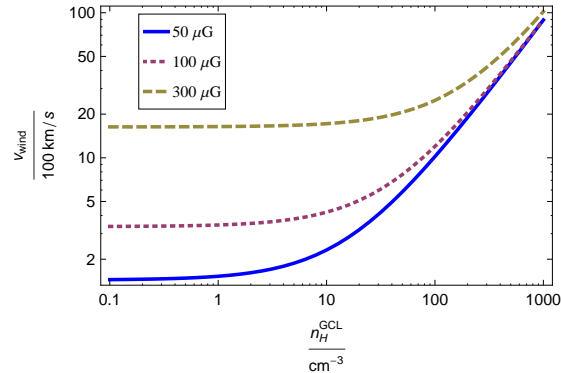


Figure 1. Lower bound on the wind speed required for electrons advected out of HESS field to synchrotron-illuminate the entire extent of the GC lobe within their loss times given by ionization, bremsstrahlung, synchrotron, and IC emission for environmental parameters of B and n_H and an interstellar radiation field energy density $U_{ISRF} \simeq 20$ eV cm $^{-3}$. We infer from Ferrière et al. (2007) that the volumetric average n_H in the GCL is ~ 10 cm $^{-3}$. The strict lower limit to the GCL magnetic field at 50 μ G (and probable value 100 μ G: Crocker et al. 2010) imply a conservative lower limit to the GC outflow speed of > 150 km/s (and probably $\gtrsim 300$ km/s).

4 NON-THERMAL HINTS OF AN OUTFLOW FROM THE GC

An important consideration is why the GC CR ion population is so hard in comparison to the diffusion-steepened, local population. There are three reasonable interpretations of this: i) the system is out of steady state with less time having passed since the CR injection event than required for diffusion steepening (cf. the interpretation adopted by Aharonian et al. 2006, that a single CR-injection event $\sim 10^4$ year ago at the GC explains the observed diminution in the γ -ray to molecular column ratio beyond $|l| \sim 1^\circ$); *or* there is a smallest relevant timescale defined by an energy-independent ii) *loss* or iii) *escape* process.

We argue here that iii) is preferred by all the evidence. We can dismiss ii) on the basis of our results above which show the system falls far short of being a calorimeter for protons. A number of factors also tell against i): firstly, as argued, other evidence indicates that the system is close to its steady state; secondly, the spectral index of the \sim TeV emission is a constant ~ 2.3 over the HESS region (within errors) presenting, therefore, no evidence of diffusion hardening at the leading edge of a (putative) diffusion sphere; and lastly, these spectral considerations apply also to the relativistic electron population: the hard radio spectrum of the region, $\alpha \lesssim 0.54$ (for $S_\nu \propto \nu^{-\alpha}$ and radio data 1.4–10 GHz: see Paper II), requires that the synchrotron-emitting electron population is also very hard, $\sim E_e^{-2.1}$. Given the rather short loss times associated with synchrotron and IC emission in the GC environment, this hard electron spectrum constitutes independent evidence for *rather quick and energy-independent CR transport* (cf. Lisenfeld & Völk 2000).

Consider then the region's non-thermal particle population which, in steady state, approximates to:

$$n_x(E_x) \simeq \frac{\tau_{\text{loss}}(E_x)\tau_{\text{esc}}}{\tau_{\text{loss}}(E_x) + (\gamma - 1)\tau_{\text{esc}}} \dot{Q}_x(E_x) \quad (3)$$

where $\dot{Q}_e(E_e)$ denotes the injection rate of particles of type $x \in \{e, p\}$; we account for both escape and energy loss over τ_{esc} and τ_{loss} with the escape time assumed to be energy-independent; and γ is the spectral index of the (assumed) power-law (in momentum) proton or electron spectrum at injection.

Turning now to the CR ion population (henceforth protons for simplicity), we have already seen that we only detect $\sim 2\%$ of the TeV γ -ray flux expected in the calorimetric limit. Given, then, that pp collisions are by far the dominant energy loss process for high-energy CR protons, this deficit implies that there is significant escape of accelerated ions (with accompanying adiabatic losses) – i.e., the system is quite far from calorimetric. We define $R_{\text{TeV}} \equiv L_{\text{TeV}}^{\text{obs}}/L_{\text{TeV}}^{\text{thick}} \simeq 10^{-2}$ (uncertain by a factor ~ 2) as the ratio of the observed flux of TeV γ -ray emission to the expected in the calorimetric limit (cf. fractions ~ 0.01 and ~ 0.05 for the Galactic disk and NGC 253; HESS Collaboration 2009). From Eq.3 and accounting for adiabatic losses with timescale $\tau_{\text{adbt}}^p = 3\tau_{\text{esc}}^p$:

$$R_{\text{TeV}} \simeq 10^{-2} \sim \frac{3\tau_{\text{esc}}^p}{3\tau_{\text{esc}}^p + 4\tau_{pp}}. \quad (4)$$

By analogy with the hadronic case, we define $R_{\text{radio}} \equiv L_{\text{synch}}^{\text{obs}}/L_{\text{synch}}^{\text{thick}} \simeq 10^{-1}$ (again uncertain by a factor ~ 2). Given the very flat radio spectral index, this deficit is potentially explained as a result of electron energy loss into bremsstrahlung, adiabatic deceleration or advective escape. Eq.3 then gives

$$R_{\text{radio}} \simeq 0.1 \sim \frac{\tau_{\text{esc}}^e(\tau_{\text{brems}} + 3\tau_{\text{esc}}^e)}{\tau_{\text{synch}}(\tau_{\text{brems}} + 4\tau_{\text{esc}}^e)}. \quad (5)$$

Now, given the foregoing, particle escape is both energy-independent and the same for CR electrons and protons ($\tau_{\text{esc}}^e \equiv \tau_{\text{esc}}^p = \text{const}$) as would be expected for a wind. This means that eq. 4 and 5 yield a combined constraint on the required velocity of the outflow responsible for particle removal: see fig. 2.

Also shown in fig. 2 are minimum and maximum values for the speed of the star-formation-driven ‘super-wind’ expected on the basis of observations of the nuclei of external, star-forming galaxies and the GC’s high areal SFR (Strickland & Heckman 2009). The asymptotic speed of such a wind scales as $v_{\text{wind}} \sim \sqrt{2 \eta \dot{E}/\dot{M}}$ where $0 < \eta < 1$ is the thermalization efficiency, typically ranging between 0.1 for relatively quiescent star formation and almost 1 for starbursts (Strickland & Heckman 2009). Adopting $\eta_{\text{min}} \equiv 0.1$, $\eta_{\text{max}} \equiv 1.0$, $\dot{E} = 1.4 \times 10^{40}$ erg/s and $0.025 M_{\odot}/\text{year}$ (see Paper II), we find $v_{\text{wind}}^{\text{min}} \simeq 400$ km/s and $v_{\text{wind}}^{\text{max}} \simeq 1200$ km/s.

Putting some of these considerations in a different form, we expect a TeV luminosity from the HESS region which satisfies $L_{\gamma}(E_{\gamma} > \text{TeV}) \sim 1/3 U_{\text{CR}}(E_p > 10 \text{ TeV})/\tau_{pp} V \leq L_{\gamma}^{\text{obs}}(E_{\gamma} > \text{TeV}) \equiv 1.2 \times 10^{35}$ erg/s where $U_{\text{CR}}(E_p > 10 \text{ TeV}) \sim 1/20 \times 1.4 \times 10^{39}$ erg/s $\times d/v_{\text{wind}}/V$ is the energy density in CR protons sufficiently energetic to generate TeV γ -rays, $d \simeq 40$ pc and $V \simeq 10^{62} \text{ cm}^{-3}$ for the HESS region, and n_H is the effective gas density the protons sample. This implies $n_H \lesssim 6 \text{ cm}^{-3}$ ($v_{\text{wind}}/1200$ km/s), cf. the volumetric average gas density through the HESS region $\sim 120 \text{ cm}^{-3}$ summing over all phases and $\sim 6 \text{ cm}^{-3}$ including only plasma phases. Likewise, the total gas mass the protons sample satisfies $M_{\text{gas}} \lesssim 5 \times 10^5 M_{\odot}$ ($v_{\text{wind}}/1200$ km/s) which is much less than the $\sim 10^7 M_{\odot}$ of gas in the region. In order

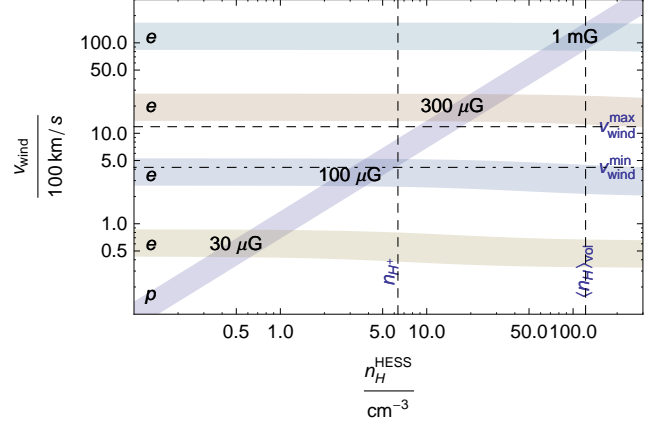


Figure 2. Outflow speed inferred given the departures from calorimetry for both protons (p) and electrons (e): $R_{\text{TeV}} = 0.01$ and $R_{\text{radio}} \simeq 0.1$ as described in the text (the width of the bands reflects the uncertainty of ~ 2 in both R_{TeV} and R_{radio}). Protons cool via their hadronic collisions with ambient gas (hence the linear dependence between wind speed and gas density, n_H) and adiabatic deceleration. In addition to bremsstrahlung (and ionization), electrons also cool via synchrotron (so the magnetic field enters as a parameter) and IC emission and adiabatic deceleration. As the wind escape time is the same for both electrons and protons, the intersection of the electron and proton bands describes a valid gas density and wind velocity for the HESS environment for each magnetic field sampled. The horizontal dashed line shows the approximate maximum allowed wind speed (~ 1200 km/s) balancing the total power assumed injected into the system by supernovae and massive stars (1.4×10^{40} erg/s) with the kinetic power advected by the wind plasma at its asymptotic velocity (assuming 100% thermalization efficiency). The horizontal dot-dashed line shows the approximate minimum plausible wind speed (~ 400 km/s) for thermalization efficiency of 10%.

that the region’s protons *not* sample all the molecular gas in the region they should be removed in a time shorter than the convection time into the dense regions of the molecular clouds: $t_{\text{wind}} \equiv d/v_{\text{wind}} < t_{\text{cloud}} \sim 10 \text{ pc}/30 \text{ km/s}$ (adopting 30 km/s as a typical internal velocity dispersion for the region’s giant molecular clouds, conservatively, of radius ~ 10 pc; e.g. Morris & Serabyn 1996) which also implies a lower limit: $v_{\text{wind}} \gtrsim 130$ km/s. Typical timescales are plotted in fig. 3.

5 DISCUSSION AND CONCLUSIONS

A clear picture emerges from the considerations above. Given the morphological and spectral data on the GC lobe, we can infer that it is illuminated with CR electrons injected in the HESS region carried from the plane on an outflow with a speed 150–1000 km/s. The spectral data on the HESS region itself imply that most CR electrons and protons accelerated in situ are advected from the region; electrons lose only $O[10\%]$ of their power to synchrotron emission in the HESS region while protons lose only $O[1\%]$ of their power to pp collisions on ambient gas in the same region.

Self-consistently and given our understanding of outflows from external, star-forming galaxies, the same star-formation and subsequent supernova processes that drive

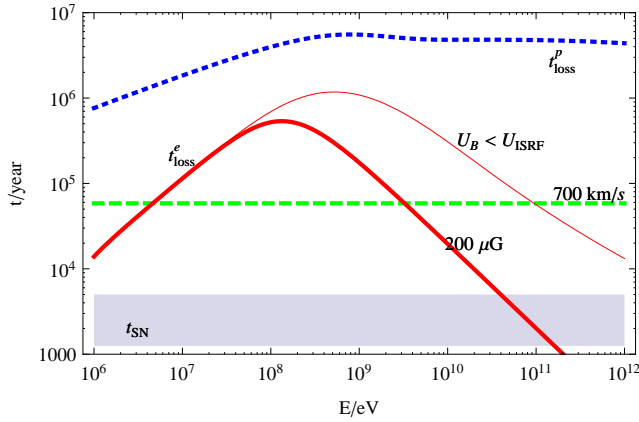


Figure 3. HESS region timescales for central parameter values suggested by our analysis, viz. $n_H = 10 \text{ cm}^{-3}$, and $v_{\text{wind}} = 700 \text{ km/s}$ with i) (horizontal solid band) the inverse of the supernova rate; ii) (dashed horizontal line) particle escape with energy-independent velocity of 700 km/s; iii) (solid red lines) electron cooling for (thick) $B = 2 \times 10^{-4} \text{ G}$ and (thin) the limiting case of vanishing magnetic field (IC cooling dominant at high energy); iv) (blue dotted line) proton cooling. Calorimetry generically requires $t_{\text{loss}} < t_{\text{esc}}$.

the thermal and non-thermal radiation from the HESS region will also drive an outflow with a speed 400–1200 km/s. This implies that the magnetic field in the HESS field lies in the range 100–300 μG and the effective gas density encountered by the CRs is in the range 3–20 cm^{-3} . The latter is much less than the volumetric average n_H over the HESS region suggesting that even super-TeV CRs do not ‘sample’ all H_2 before escaping the region.

We suspect that the outflow we identify plays many important roles (see Paper II and Crocker & Aharonian 2010) including advecting positrons into the Galactic bulge (thereby explaining the $\sim\text{kpc}$ extension of the 511 keV annihilation radiation: Weidenspointner et al. 2008), carrying CR ions accelerated by GC supernovae out to very large heights ($\sim 10 \text{ kpc}$) thereby explaining the WMAP ‘haze’ and Fermi ‘bubbles’ (Finkbeiner et al. 2004; Dobler et al. 2010; Su et al. 2010; Crocker & Aharonian 2010), and generally keeping the energy density of the non-thermal components of the GC ISM in check (Breitschwerdt et al. 2002).

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